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INVESTIGATION OF URBAN WATER QUALITY USING ARTIFICIAL RAINFALL

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ABSTRACT

As the concept of sustainable communities is gaining increasing recognition around the world it is of critical importance to investigate the water quality of urban environments. The contamination of waterways in urban communities seriously affects the utility of water for different purposes and degrades the aesthetic value of natural watercourses. Research investigations in the past have generally focused on suspended solids and nutrients, which are relatively easy to monitor. Unfortunately the build-up and wash-off of micro pollutants such as polycyclic aromatic hydrocarbons (PAH) and heavy metals (HM) have received limited research interest in urban water quality research even though these can cause significant health and environmental impacts even at low concentrations. This paper describes how artificial rainfall, using a specially designed highly portable rainfall simulator was employed in order to generate water quality data from urban environments. This approach was adopted in order to investigate the wash-off of pollutants from paved surfaces and to overcome constraints due to the highly unreliable rainfall in South-East Queensland Australia. The rainfall simulator was able to demonstrate its ability to satisfactory simulate natural rainfall in the area. The results obtained confirmed that the rainfall simulator is a reliable tool for urban water quality research and can be used to simulate pollutant wash-off.

Keywords: Rainfall simulation, Urban water quality, Urban stormwater pollution, Water quality research

INTRODUCTION

Stormwater runoff from urban areas is a major non-point source of pollutants (Pitt et al. 1996). The process kinetics of pollutant build-up and wash-off in urban areas is complex. Multiple variables and processes influence the generation and transport of pollutants. The relative importance of these factors is difficult to evaluate and can be highly variable in an urban environment (House et al. 1993). These issues act as significant constraints in the transferability of the research outcomes and have resulted in inadequate knowledge of the build-up and wash-off process kinetics of persistent pollutants such as Polycyclic Aromatic Hydrocarbons (PAHs) and heavy metals. Under these circumstances, the adoption of research methodologies commonly used in other disciplines such as agriculture should be considered in order to overcome these problems.

Catchment studies are important for calibration and validation purposes. However due to the heterogeneity of urban areas, they are not particularly suitable for the development of fundamental concepts and relationships. The use of small test plots to ensure homogeneity and approaches such as artificial rainfall simulation will help to reduce the large number of variables and lessen the location specific nature of the outcomes usually inherent to urban water quality research. Though rarely used in urban water quality research, the use of rainfall simulation offers the opportunity to generate a reliable database for undertaking complex investigations. Rainfall simulation is an important tool in agricultural research, such as erosion and infiltration studies (Loch et al. 2001). It is a time and cost efficient method to overcome the dependency on natural rainfall events.

This paper describes how rainfall simulation was used to generate a reliable database in order to investigate parameters that influence the build-up and wash-off of PAHs and heavy metals in an urbanized area. A number of rainfall events were simulated and the samples collected were analysed for a range of variables.

DESIGN OF THE RAINFALL SIMULATOR

The design of a simulator to replicate natural rainfall is complex and involves many characteristics including drop sizes and rainfall intensities. A wide range of rainfall simulators have been designed and successfully used in past research. However, the design of a rainfall simulator is dependant on the focus of the individual research and the need to satisfy specific criteria (Meyer 1988). Therefore, a rainfall simulator used for urban water quality research has to be based on criteria such as runoff sample collection efficiency, rainfall intensity and event duration.

To date, only limited attention has been given to collecting runoff from paved surfaces under field conditions. Vaze and Chiew (1997) used a plywood frame with a hole dug at the outlet to place sample bottles for collecting runoff. This is not practical for investigating urban water quality in a roadway. In the alternative, if a vacuum system is to be used for sample collection, its efficiency in picking up small size particles is an important issue. Small particles act as a mobile substrate for other pollutants (Tai 1991). Bris et al. (1999) for example found that the vacuum system used by them was not satisfactory and had to resort to additional manual brushing of the road surface. Clearly, an effective sample collection system is a major factor in rainfall simulation on paved surfaces.

The rainfall simulator used for this research as shown in Figure 1 was designed to meet the following primary requirements:

- complete portability, easy assembly and operation;
- drop-size distribution, terminal velocity and kinetic energy similar to natural rainfall;
- ability to replicate rainfall intensities suitable for the proposed research study;
- ability to apply rainfall uniformly over the plot area;
- satisfactory system for runoff collection from paved surfaces.

The rainfall simulator can be easily dismantled and fitted to a conventional 750 kg capacity box trailer for transport to the field. Three nozzles, spaced one metre apart, are mounted on a stainless steel boom such that the nozzle spray height is 2.4m. This height is adequate for creating terminal velocities similar to natural rainfall for all drop sizes (Duncan 1972). The runoff water is collected in a trough and is vacuumed continuously into 25L containers and sub-sampled into 1L sample bottles during the run. A bagless vacuum cleaner with water filtration is used for collecting the runoff. The vacuum cleaner was selected after evaluation of a wide range of commercially available products.

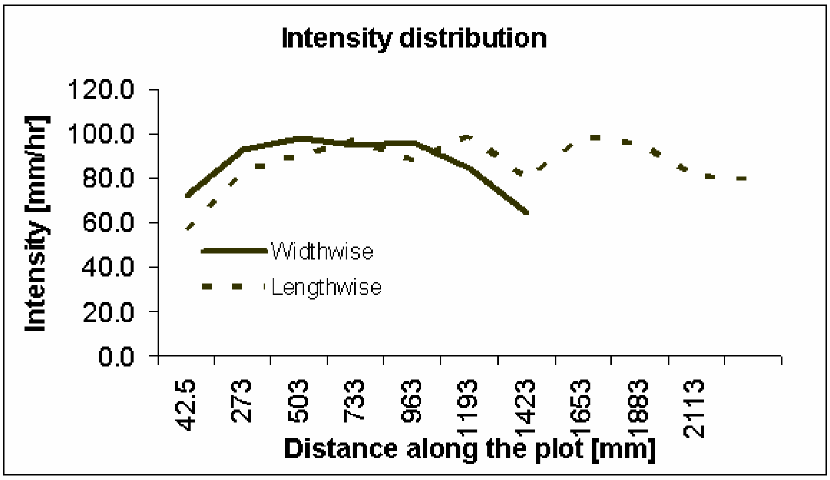
Figure 1 – The developed rainfall simulator

The rainfall simulator has been calibrated in several stages. Initially starting with 12 nozzles, the discharge rate and the spray patterns were investigated to identify the three most similar nozzles. Discharge rate was measured using a container to collect water from the spray nozzle during a set time period whilst the spray patterns were evaluated using a grid pattern of beakers placed on the ground (Loch et al. 2001).

The next step consisted of calibrating the simulator for intensity, uniformity of rainfall and drop-size. Intensity and uniformity were measured using beakers kept in a grid pattern and measuring the rainfall volumes collected over a range of intensities and durations. The median drop size (d_{50}) of the simulated rainfall was measured using the flour pellet method described by Hudson (1963). The median drop size for the simulated rainfall was calculated as 2.1mm. The kinetic energy was determined to be 25.44 J/m^{2}mm based on Laws' (1941) data on terminal drop velocities. The values obtained were found to be a satisfactory replication of natural rainfall characteristics in the area (Rosewell 1986).

Based on selected Average Recurrence Intervals (ARI), the uniformity of rainfall for a number of design rainfall intensities was investigated. The major component of spatial variability was along the longitudinal axis of the plot, with peaks under the nozzles and troughs between them. This was minimised by overlapping the spray patterns, but still caused some variation as shown in Figure 2. However, by judicious selection of the plot size, these effects can be minimised. The plot area chosen had dimensions of 2x1.5 m and an average Coefficient of Uniformity (Cu) of 95% (Christiansen 1942). Cu is defined as the deviation of individual observations from mean over the mean value and number of observations. A high Cu value indicates small deviation from the mean intensity. The impact of rainfall intensity on Cu was found to be negligible.

Figure 2 – Nozzle intensity distribution



The efficiency of the vacuum system for runoff collection was evaluated using a soil sample with fractions of known particle sizes between 0.5µm and 3,350µm. A bitumen slab was used as a test surface for the application of the soil. After four longitudinal sweeps of the vacuum cleaner, its collection efficiency was calculated. The vacuum system was proven to have an overall efficiency of 91%, including a 2% loss of particles in the vacuum hoses.

In order to re-produce natural rainfall characteristics as closely as possible, the chemical quality of rainfall in the proposed study region was investigated. Water collected in rainwater tanks was not considered due to the risk of unwanted pollutants, particularly if it was collected from metal roofs. Consequently, rainwater samples were collected over a period of time and a quality profile was developed based on statistical analysis of the sample data. Rainwater samples were tested for pH, Electrical Conductivity (EC) and Dissolved Organic Carbon concentration (DOC). These parameters are important due to their ability to influence the physico-chemical quality characteristics of stormwater runoff (Warren et al. 2003). pH influences the bio-availability of heavy metals (Tai 1991). Similarly, organic carbon influences the concentration of Polycyclic Aromatic Hydrocarbons present in the dissolved phase (Wang et al. 2001). EC is important due to its ability to enhance the adsorption affinity of solid particles (Pechacek 1994). Deionised water was spiked with sulphuric acid (for pH), common salt (for EC) and methanol (for DOC) to obtain the required water quality profile for the rainfall simulations.

STUDY AREA

The rainfall simulator was employed to replicate a range of rainfall events at three research sites with different landuses. At all three sites, the quality of the surface runoff from paved surfaces were investigated as past research has identified road surfaces as the primary pollutant source in urban areas (Pauleit and Duhme, 2000; Sartor and Boyd, 1972; Shaheen, 1975).

The research sites were located in the Gold Coast region just south of the Queensland State capital, Brisbane, Australia. Gold Coast region is a popular holiday destination and has one of the highest growth rates in the country. It has a subtropical climate with wet summers and dry winters and a varying topography covering both the south-eastern coastline of Australia and the hinterland. The vast majority of rainfall occurs during the summer months of December to February.

Figure 3a – Residential research site (Millswyn Crescent)

Research site 1 shown in Figure 3a was an access road (Millswyn Crescent) located in a typical suburban residential area (Residential A) with detached family houses with small gardens. The road system is primarily used by the residents, which is reflected in the relatively satisfactory condition of the street surface. An early investigation of the households suggested that various chemicals were used as fertilizers or for other uses and therefore could be incorporated into the wash-off from the area. It was also found that street sweepers operate in the area every six weeks, which may influence the availability of pollutants on the road surface at certain times.

Research site 2 shown in Figure 3b (Stevens Street) was located in an industrial area. The site was chosen because of the diversity of industries located along the road. Industries at the site include a sheet metal works, a boat painter, a furniture manufacturer and other small enterprises. The street surface condition compared to the residential site was significantly degraded.

Research site 3 shown in Figure 3c was a parking lot in a major shopping centre. The shopping centre is strategically positioned in an area which has one of the highest growth rates in the Gold Coast region. The shopping centre has 570 parking spaces and considered to be one of the busiest in the region with 45 specialty retailers in the complex. The condition of the parking lot was found to be fair but with a coarse texture. The coarse texture suggested that a large number of particles would be embedded in the voids and available for wash-off.

Figure 3b – Industrial research site (Stevens Street)

Figure 3c – Commercial research site (Centro Nerang Shopping Centre)

SAMPLE COLLECTION

The field work consisted of collecting build-up and wash-off samples. Initially the sampling of pollutant build-up on the road surface was carried out using the vacuum cleaner. An area of 2x1.5m situated between the kerb and the median strip of the road was vacuumed four times. The vacuum cleaner and hose was carefully cleaned with deionised water after the build-up material was collected. The collected material was then transferred into 1L polyethylene bottles and kept in storage for transport to the laboratory.

The rainfall simulator was assembled at the wash-off plot just upstream of the build-up plot location. The runoff plot was spaced the same distance from the kerb and middle strip as the build-up plot. Due to time limitations and the large number of rainfall events that needed to be simulated in one day, only one build-up plot per site was used. The pollutant availability was therefore assumed to be the same for all events at each individual site. Due to the relatively short distance between each plot this assumption was considered to be reasonable. Figure 4 shows the sampling of wash-off using the rainfall simulator at the industrial site.

Figure 4 – Collection of runoff samples at Industrial site

Runoff samples were collected continuously during the event. Rainfall events and collection efficiencies as compared to the total rainfall for the test events are presented in Table 1 below. The runoff samples collected were transferred from the 25L collection containers to 1L poly-ethylene bottles except for samples analysed for PAHs which were collected in amber glass bottles with Teflon-lined screw-caps as specified in Standard Methods for Water and Wastewater (Eaton et al. 1999).

The low collection efficiency for a number of events at site 3 was due to a small natural rainfall event wetting the surface at the time. Even though every effort was made to ensure the surface was dry, the moisture on the surface at site 3 and the coarse texture depth made it difficult to seal the interface between the collection trough and the road surface. However, as the decrease in collected runoff would only affect the pollutant load, it was assumed that the pollutant concentration would not be significantly influenced by the volume of runoff.

Table 1 – Runoff collection efficiency

Event ARI/duration	Collection efficiency site 1 [%]	Collection efficiency site 2 [%]	Collection efficiency site 3 [%]
1year/20min	No data	85.4	36.9
2year/35min	No data	85.6	35.1
10year/65min	No data	82.5	34.6
1year/10min	96.5	90.0	93.0
2year/20min	97.0	93.8	90.7
10year/40min	97.0	91.1	84.3
1year/5min	76.9	88.0	38.3
2year/10min	72.9	87.3	40.0
10year/20min	92.9	No data	33.4
2year/7min	60.7	94.2	96.7
5year/13min	62.6	96.8	100
10year/17min	75.1	97.3	100

A 1L Event Mean Concentration (EMC) sample for each event, including the build-up sample, was used to partition the sample into a dissolved phase and a particulate phase. Flow weighted samples such as EMC-samples were considered to be adequate in terms of determining the concentration of pollutants during a rainfall event. Each sample was analysed according to Standard Methods as shown in Table 2.

Table 2 – Methods for analysing pollutants

Parameter	Method no (Eaton et al. 1999)	Comments
pH	Not specified	Combined pH/EC-meter was used
EC	2520B	Combined pH/EC-meter was used
Organic Carbon	5310B	A Shimadzu TOC-5000A Total Organic Carbon analyser was used.
Total Suspended Solids	2540D	Samples were filtered using a 0.45µm nitrocellulose filter. Filtrate was used to measure Total Dissolved Solids
Heavy metals	3030E, 3120B	Digestion with nitric acid. Analysis by Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS). Eight elements (Zn, Fe, Al, Cr, Cd, Mn, Cu, Pb).
PAHs	6440B	16 species. Particulate matter was extracted using sonication. Analysis by Gas Chromatography – Mass Spectroscopy using a ThermoFinnigan PolarisQ GC/MS.

DATA ANALYSIS AND DISCUSSION

The residential site was chosen as a case study to determine the ability of the rainfall simulator to replicate natural rainfall. Data from a small gauged catchment (Alextown) in the region containing only town houses and a high impervious surface area was used to compare the process kinetics of pollutant wash-off. In order to evaluate the efficiency of rainfall simulation in generating an urban stormwater database, a number of parameters were compared in dissolved and particulate samples from Alextown as well as the rainfall simulator runoff samples. Patterns and trends were then analysed in the Alextown samples using Principal Component Analysis (PCA), which is a method to identify correlations among variables (Bengraïne and Marhaba, 2003; Farnham et al, 2003). The PCA analysis revealed variables which significantly influence water quality characteristics. The rainfall simulator samples from the residential site were then analysed accordingly to ensure that similar correlations or relationships occurred.

Total and dissolved concentrations were used for the comparison analysis. The mean concentration for each parameter and the standard deviation from the mean concentration for each site is shown in Table 3 and 4 respectively.

Table 3 – Dissolved concentrations in analysed samples from each site

Parameter	Alextown		Millswyn	
	Mean value	Standard deviation	Mean value	Standard deviation
pH	6.617	0.185	6.979	0.186
EC [μS/cm]	66.655	25.200	116.378	10.060
TDS [mg/L]	121.818	87.315	77.778	10.830
DOC [mg/L]	11.085	2.334	7.451	1.308
Zn [mg/L]	0.059	0.016	1.400	0.959
Al [mg/L]	0.053	0.055	0.003	0.003
Cu [mg/L]	0.005	0.001	0.092	0.202
Fe [mg/L]	0.044	0.033	0.005	0.009
Mn [mg/L]	<0.001	-	0.004	0.001
PAHs [μg/L]	1.514	0.809	0.129	0.067

Table 4 – Total concentrations in analysed samples from each site

Parameter	Alextown		Millswyn	
	Mean value	Standard deviation	Mean value	Standard deviation
pH	6.617	0.185	6.979	0.186
EC [µS/cm]	66.655	25.200	116.378	10.060
TSS [mg/L]	78.243	60.249	42.763	32.933
TOC [mg/L]	30.764	47.967	8.790	1.599
Zn [mg/L]	0.140	0.081	1.593	0.971
Al [mg/L]	1.225	0.935	0.747	0.436
Cu [mg/L]	0.018	0.015	0.420	0.136
Fe [mg/L]	1.281	0.856	0.982	0.497
Mn [mg/L]	0.028	0.018	0.024	0.009
Pb [mg/L]	0.008	0.008	0.008	0.005
Cd [mg/L]	0.001	0.002	0.079	0.218
Cr [mg/L]	0.010	0.007	0.017	0.004
PAHs [µg/L]	20.838	11.106	0.500	0.262

The number of principal components to be used in the analysis was determined by scree plots, which shows the total variance of the components. Three principal components covered 85% to 90% of the total variance in all cases and were used in the analysis. Figure 5 below shows the total variance of the principal components in the dissolved samples at Millswyn Crescent. All raw data used in the PCA analysis was subjected to pre-treatment in order to remove or reduce extraneous sources of variation or 'noise' which may interfere in the analysis. Pre-treatment included log transformation of the dissolved sample concentrations and standardization by mean centering each column of both the dissolved and total sample concentrations (Kokot et al.. 1998).

Ten variables were chosen to identify patterns and trends in the dissolved samples. The variables chosen were pH, EC, Dissolved Organic Carbon (DOC), Zn, Cu, Mn, Fe, Al, Total Dissolved Solids (TDS) and total PAHs. Some of the heavy metals species investigated were below detection limits in the dissolved phase.

As can be seen in Figure 6, pH seems to have no significant effect on the dissolved concentrations of heavy metals and PAHs at Millswyn Crescent as shown by the approximately 90^o angle between the pH-vector (dotted line) and the PAH-vector and the heavy metal-vectors. A 90^o angle indicates no correlation between variables in a PCA loading plot (Kokot et al., 1998). However, as seen in Figure 6, DOC and EC were correlated with the heavy metals and the total concentration of PAHs in the dissolved sample. Al and Fe were closely correlated, and similarly Zn, Cu and PAHs. TDS was closely correlated with Zn, Cu and PAHs.

The dissolved samples from Alextown showed similar results as can be seen in Figure 7. Once again, pH had no effect on heavy metal and PAH concentrations. EC and DOC on the other hand, were correlated with PAHs and most heavy metals, although the pattern is somewhat different to Millswyn Crescent. Al and Fe were closely correlated once again. Zn show a slightly different pattern in Alextown samples compared to Millswyn Crescent but still showed correlation to both EC and DOC. Total Dissolved Solids had a similar pattern as in the Millswyn Crescent samples although Zn and Cu seemed to be less correlated with TDS at the Alextown site than the Millswyn Crescent site. PAH concentrations and Mn concentrations in the Alextown dissolved samples were very low. Hence their loading was significantly lower than other species on the plot, which may affect the loading plot slightly.

Figure 5 – Scree plot for the dissolved sample from Millswyn Crescent

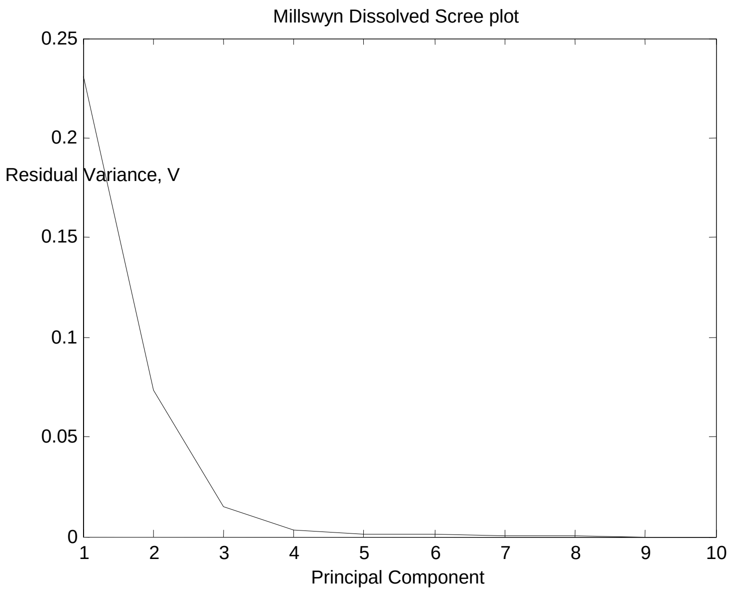
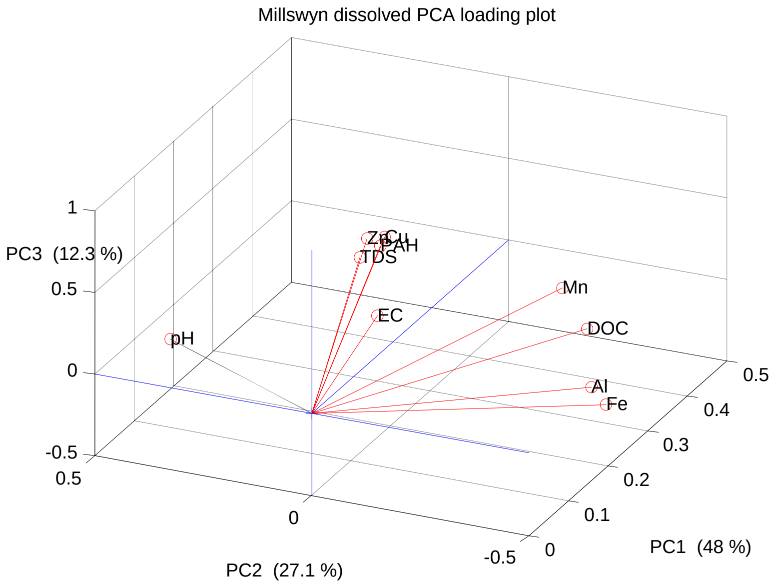


Figure 6 – PCA loading plot of pollutants in dissolved samples from Millswyn Crescent



Thirteen variables were chosen as components in the comparison of the total concentrations from each site. The variables were similar to the dissolved sample variables except for DOC which was replaced by TOC and TDS which was replaced by TSS. Three more elements of heavy metals were also added (Cd, Cr and Pb).

Once again, pH had a negligible effect on the concentration of pollutants compared to other variables in the Millswyn Crescent samples. As can be seen in Figure 8, the total concentration of most of the heavy metals in Millswyn Crescent samples except Zn, Cu and Cd, were correlated with the concentration of TOC and TSS. This is not altogether surprising since Zn and Cu are often found to dominate in the dissolved phase of stormwater runoff (Morrison et al., 1984; Sansalone and Buchberger, 1997).

Figure 7 - PCA loading plot of pollutants in dissolved samples from Alextown

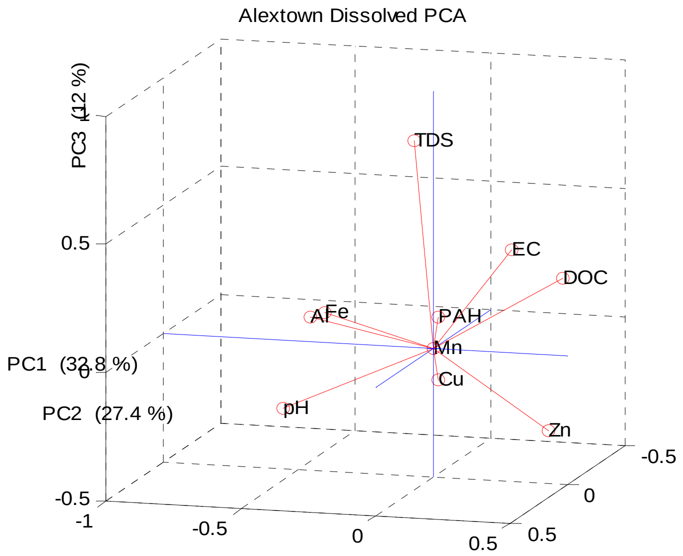
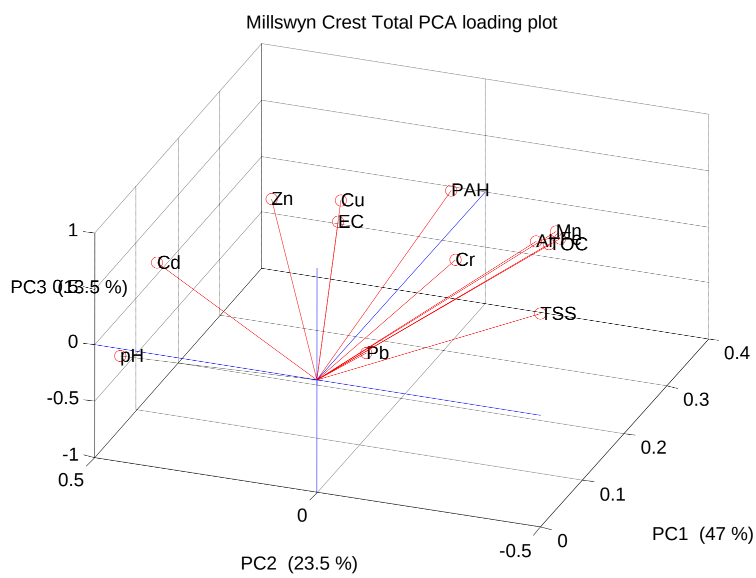


Figure 8 - PCA loading plot of total pollutant concentrations in samples from Millswyn Crescent

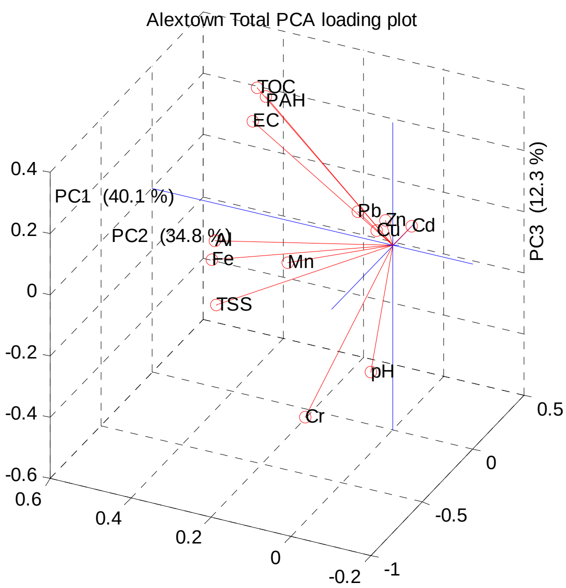


Zn and Cu total concentrations were more affected by the EC. The only heavy metal that appeared to be slightly affected by a change in pH was Cd. However, the variation of pH in the samples was low overall compared to TSS and EC which explains the low correlation of heavy metal concentrations with pH. Total PAH concentrations showed correlations with EC, TOC and TSS. The total organic carbon (TOC) also seemed to have an effect on total PAH concentrations.

As a comparison, the total concentrations of the same variables were analysed in the Alextown samples. Figure 9 shows clearly how similar patterns can be found in Alextown samples as those found in samples collected with the rainfall simulator at Millswyn Crescent. Zn and Cu total concentrations were again correlated with EC and Al, Fe and Mn total concentrations with TSS. PAH concentrations again showed dependence on EC, TOC and to a certain aspect TSS. The only variation compared to the Millswyn samples were found in Cr and Cd concentrations. At Millswyn Crescent, Cd concentrations were clearly correlated with the pH. However, in Alextown samples it was also being noted that Cr concentration was dependant on pH changes. However, this could be explained by the use of two different sites for the comparison study. Also it is possible that in addition to the runoff from paved in areas in Alextown there could be other areas also contributing to the runoff. Consequently, perfect match in water quality would have been impossible to achieve.

It is also important to note that artificial rainfall has certain limitations compared to natural rainfall. Runoff from natural rainfall includes both wet and dry deposited pollutants. Runoff resulting from rainfall simulation can only incorporate the dry deposited pollutants as any pollutants available in the atmosphere will not be washed out.

Figure 9 - PCA loading plot of total pollutant concentrations in samples from Alextown



CONCLUSIONS

A specially designed rainfall simulator was developed to investigate pollutant wash-off from paved surfaces in urban areas. Data obtained from the simulations and from natural rainfall events were compared using principal component analysis. It was possible to validate that the rainfall simulator is able to satisfactorily replicate natural rainfall events. These findings suggest that the use of rainfall simulation in urban water quality research can be a both time and cost efficient approach to developing a suitable database. Although rainfall simulation has been primarily used in agricultural research, the techniques used can be applied to urban water quality research on paved surfaces.

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